Supplemental material for: A large-momentum-transfer Raman atom interferometer without k-reversal

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In an atom interferometer, the probability of detecting atoms in one of two output states is determined by the difference in the phases, $\Delta\phi$, accumulated along the two arms. Our $\Delta\phi$ is proportional to the acceleration of the atoms relative to the mirror that retro-reflects the laser light. Vibrations of the mirror are fast enough that the acceleration changes during the interferometer sequence, and therefore we need to consider what kind of average determines $\Delta\phi$. In the case of a standard three-pulse Mach-Zehnder (MZ) interferometer, the acceleration is averaged with a triangular weighting factor [1]. Here we derive the appropriate weighting function for our $4\hbar k$ large momentum transfer (LMT) interferometer and consider how to generalise it to other schemes.

To derive the weighting, we firstly review each of the three phase contributions to the total phase difference, $\Delta\phi_{\mathrm{LMT}}$, for our $4\hbar k$ LMT interferometer. We then show the acceleration weighting function of our $4\hbar k$ LMT interferometer is trapezoidal rather than a triangle. Finally, we provide a simple picture to understand the shape of an acceleration weighting function. This picture provides an intuitive way to obtain the acceleration weighting function for an arbitrary pulse sequence, such as a $4N\hbar k$ LMT interferometer proposed in Fig. 5 in the main text.

PHASE CONTRIBUTIONS

Assuming all the ^{87}Rb atoms are prepared in the F=1 state before the interferometer pulses, then the final population in F=2, $P_{F=2}$, at the output of our $4\hbar k$ interferometer is given by

$$P_{F=2} = B - A\cos(\Delta\phi), \tag{I}$$

where B is the middle point of the interference fringe, A is the amplitude of the fringe and $\Delta\phi$ is the total phase difference between two interferometer arms.

Following the formalism and notation in [2], we can calculate this total phase difference, $\Delta\phi$, by separating it into three contributions

$$\Delta\phi = \Delta\phi^{\mathrm{prop}} + \Delta\phi^{\mathrm{sep}} + \Delta\phi^{\mathrm{int}}, \tag{II}$$

where $\Delta\phi^{\mathrm{prop}}$ is the difference of the propagation phase between the two interferometer arms, $\phi_\ell^{\mathrm{prop}}$ and $\phi_{\mathrm{r}}^{\mathrm{prop}}$. We use the same ℓ/r (left/right) notation for the separation phase difference, $\Delta\phi^{\mathrm{sep}}$, and the interaction phase difference, $\Delta\phi^{\mathrm{int}}$.

We note that $\Delta\phi^{\mathrm{sep}} = 0$ for our interferometer, as we have chosen $T_1 = T_4$ such that for the final pulse the two interferometer arms overlap in space, closing it. Thus, we only need to calculate the sum of $\Delta\phi^{\mathrm{prop}}$ and $\Delta\phi^{\mathrm{int}}$ to evaluate $\Delta\phi$.

Propagation phase

The propagation phase originates from the free-evolution of the wave packet and it is given by

$$\Delta\phi^{\mathrm{prop}} = \underbrace{\sum_{\mathrm{right}} \int_{t_I}^{t_F} \frac{L_c - E_i}{\hbar} dt}_{\phi_{\mathrm{r}}^{\mathrm{prop}}} - \underbrace{\sum_{\mathrm{left}} \int_{t_I}^{t_F} \frac{L_c - E_i}{\hbar} dt}_{\phi_\ell^{\mathrm{prop}}}, \tag{III}$$

where the sum is over all segments of the left (or right) path, L_c is the classical Lagrangian evaluated at the centre of mass of the wavepacket on the left (or right) trajectory, E_i is the internal atomic energy on that trajectory, and t_I and t_F are the initial time and the final time of each path segment.

In our interferometer, the contribution of L_c is found to be zero. Therefore, $\Delta\phi^{\mathrm{prop}}$ is determined by the energy difference of the two internal states, $\omega_0 = (E_2 - E_1)/\hbar$, and the time spent in each internal state, given by

$$\Delta\phi^{\mathrm{prop}} = -\omega_0 (\tilde{T}_1 - T_1 + T_2 - T_3 + T_4 - \tilde{T}_2), \tag{IV}$$

where $\tilde{T}_1, T_1, T_2, T_3, T_4$ and $\tilde{T}_2$ are the temporal separations between interferometer pulses shown in Fig. 1b in the main text.

Interaction phase

The interaction phase comes from the phase of the microwave field or Raman laser imprinted on the wavepacket during a coherent population transfer. The difference in the interaction phases accumulated on the two interferometer arms is given by

$$\Delta\phi^{\mathrm{int}} = \underbrace{\sum_j \pm\phi^{\mathrm{int}}\big(x_{\mathrm{r}}(t_j), t_j\big)}_{\phi^{\mathrm{int}}_{\mathrm{r}}} - \underbrace{\sum_j \pm\phi^{\mathrm{int}}\big(x_{\ell}(t_j), t_j\big)}_{\phi^{\mathrm{int}}_{\ell}}, \tag{V}$$

where the summation is over all the interaction events, which occur at times t_j and at positions $x_{\mathrm{r}}(t_j)$ and $x_\ell(t_j)$ on the classical trajectories. We will further split the interaction phase ϕ^{int} out according to whether it arises from a microwave transition or a Raman transition, ϕ^{M} and ϕ^{R} respectively. The interaction phase has a $+(-)$ sign when a photon is absorbed(emitted) by an atom.

The microwave phase at an atom's center of mass position $\mathbf{x}_c$ at time t is given by

$$\phi^{\mathrm{M}} = \omega^{\mathrm{M}} t - \mathbf{k}^{\mathrm{M}} \cdot (\mathbf{x}_c(t) - \mathbf{x}_{\mathrm{horn}}) + \varphi^{\mathrm{M}}, \tag{VI}$$

where ω^{M}, $\mathbf{k}^{\mathrm{M}}$ and φ^{M} are the frequency, wavevector, and a constant initial phase of the microwave field. We assume the position of the horn $\mathbf{x}_{\mathrm{horn}}$ is static. Similarly, the Raman phase is given by

$$\phi^{\mathrm{R}} = \omega^{\mathrm{R}} t - \mathbf{k}^{\mathrm{R}} \cdot \big(\mathbf{x}_c(t) - \mathbf{x}_{\mathrm{mirror}}(t)\big) + \varphi^{\mathrm{R}}, \tag{VII}$$

where ω^{R}, $\mathbf{k}^{\mathrm{R}}$ and φ^{R} are the frequency, wavevector and a constant initial phase of the Raman light. $\omega^{\mathrm{R}} = \omega_1 - \omega_2$ is the frequency difference between the two Raman lasers and $\mathbf{k}^{\mathrm{R}} = \mathbf{k}_1 - \mathbf{k}_2$ has a magnitude of $2k$, where $k = 2\pi/\lambda$ is the averaged wavenumber of two Raman lasers of wavelength $\lambda \approx 780\,\mathrm{nm}$. The position of the retroreflection mirror $\mathbf{x}_{\mathrm{mirror}}$ can vary in time. Its acceleration is monitored by the MEMS accelerometer.

In our $4\hbar k$ interferometer, the interaction phases accumulated along each arm are given by

$$\begin{aligned}
\phi^{\mathrm{int}}_r =& \phi^{\mathrm{R}}_{2,r} - \phi^{\mathrm{R}}_{3,r} + \phi^{\mathrm{M}}_{4,r} - \phi^{\mathrm{R}}_{5,r} + \phi^{\mathrm{R}}_{6,r},\\
\phi^{\mathrm{int}}_\ell =& \phi^{\mathrm{M}}_{1,\ell} - \phi^{\mathrm{R}}_{2,\ell} + \phi^{\mathrm{R}}_{3,\ell} - \phi^{\mathrm{M}}_{4,\ell} + \phi^{\mathrm{R}}_{5,\ell} - \phi^{\mathrm{R}}_{6,\ell} + \phi^{\mathrm{M}}_{7,\ell},
\end{aligned} \tag{VIII}$$

where we have labeled each phase contribution $\phi^{\mathrm{X}}_{j,\alpha}$ with X denoting Raman or MW, j denoting pulse number, and α the left or right arm. Substituting equations Eq.VI to Eq.VIII into Eq.V gives the interaction phase difference between the two arms of our interferometer:

$$\begin{aligned}
\Delta\phi^{\mathrm{int}} =& \omega^{\mathrm{M}}(-t_1 + 2t_4 - t_7)\\
&+ \mathbf{k}^{\mathrm{M}} \cdot \big(\mathbf{x}^{\mathrm{M}}_{1,\ell} - \mathbf{x}^{\mathrm{M}}_{4,\ell} - \mathbf{x}^{\mathrm{M}}_{4,\mathrm{r}} + \mathbf{x}^{\mathrm{M}}_{7,\mathrm{r}}\big)\\
&+ 2\omega^{\mathrm{R}}(t_2 - t_3 - t_5 + t_6)\\
&- 2\mathbf{k}^{\mathrm{R}} \cdot \big(\bar{\mathbf{x}}^{\mathrm{R}}_2 - \bar{\mathbf{x}}^{\mathrm{R}}_3 - \bar{\mathbf{x}}^{\mathrm{R}}_5 + \bar{\mathbf{x}}^{\mathrm{R}}_6\big),
\end{aligned} \tag{IX}$$

where we use the averaged classical atom position relative to the mirror, $\bar{\mathbf{x}}^{\mathrm{R}}_{\mathrm{j}}$:

$$\begin{aligned}
\mathbf{x}^{\mathrm{R}}_{\ell,r}(t_j) &= \mathbf{x}_{\ell,r}(t_j) - \mathbf{x}_{\mathrm{mirror}}(t_j),\\
\bar{\mathbf{x}}^{\mathrm{R}}_{\mathrm{j}} &= \frac{\mathbf{x}^{\mathrm{R}}_{\ell}(t_j) + \mathbf{x}^{\mathrm{R}}_{r}(t_j)}{2}.
\end{aligned} \tag{X}$$

Total phase difference between two arms

The total phase difference between the two interferometer arms can be calculated by substituting Eq.IV and Eq.IX into Eq.II. Noting that we closed the interferometer by choosing $T_1 = T_4$, we can separate the microwave and Raman contributions and express $\Delta\phi$ as

$$\Delta\phi = \Delta\phi^{\mathrm{M}} + \Delta\phi^{\mathrm{R}}, \tag{XI}$$

which is the same form as that of the Eq. 1 in the main text. Then, the microwave phase difference and the Raman phase difference are

$$\begin{aligned}
\Delta\phi^{\mathrm{M}} =& (\omega^{\mathrm{M}} - \omega_0)\left((\tilde{T}_1 + T_1 + T_2 - (T_3 + T_4 + \tilde{T}_2)\right)\\
&+ \mathbf{k}^{\mathrm{M}} \cdot \big(\mathbf{x}^{\mathrm{M}}_{1,\ell} - \mathbf{x}^{\mathrm{M}}_{4,\ell} - \mathbf{x}^{\mathrm{M}}_{4,\mathrm{r}} + \mathbf{x}^{\mathrm{M}}_{7,\mathrm{r}}\big),\\
\Delta\phi^{\mathrm{R}} =& 2\,(\omega^{\mathrm{R}} - \omega_0)(T_4 - T_1)\\
&- 2\mathbf{k}^{\mathrm{R}} \cdot \big(\bar{\mathbf{x}}^{\mathrm{R}}_2 - \bar{\mathbf{x}}^{\mathrm{R}}_3 - \bar{\mathbf{x}}^{\mathrm{R}}_5 + \bar{\mathbf{x}}^{\mathrm{R}}_6\big).
\end{aligned} \tag{XII}$$

We assume that in the horizontal direction, the atoms have some constant acceleration a, and that the scale of the horizontal trajectories, which is about 800 μm, is much less than the microwave wavelength of 4.4 cm. In addition, the standing wave form of the microwave in our system allows us to ignore the spatially dependent part of the microwave phase in Eq. XII to re-write the microwave phase difference between the two arms as:

$$\Delta\phi^{\mathrm{M}} = \delta^{\mathrm{M}}\,(\tilde{T}_1 + T_2 - T_3 - \tilde{T}_2), \tag{XIII}$$

where $\delta^{\mathrm{M}} = \omega^{\mathrm{M}} - \omega_0$ is the microwave detuning, and we have used $T_1 = T_4$ for our closed interferometer. This is the derivation of Eq. 2 in the main text.

To derive Eq. 3 we assume a symmetric pulse sequence such that $\tilde{T}_1 = \tilde{T}_2$ and $T_2 = T_3$ in addition to $T_1 = T_4$ required by a closed interferometer, which simplifies the Raman phase difference to

$$\begin{aligned}
\Delta\phi^{\mathrm{R}} =& a\,T_1(T_1 + T_2 + T_3)\\
=& a\,\frac{T_1}{T}\left(2 - \frac{T_1}{T}\right)4k\,T^2.
\end{aligned} \tag{XIV}$$

We have used $T_2 = T - T_1$ to show how $\Delta\phi$ depends on the separation between the first two Raman pulses, T_1, and the time between the first and the last Raman pulses, $2T$. Dividing T_1 by T makes it simple to compare the acceleration sensitivities of the LMT and MZ interferometers.

ACCELERATION WEIGHTING FUNCTION

Phase noise from vibrations has been well-studied [1] in a three-pulse MZ interferometer, where only the laser phase contributes to the total interferometer phase $\Delta\phi_{\rm MZ}$. We apply the same formalism to our LMT interferometer. Although our interaction phase consists of both the Raman laser phase and the microwave phase, only the Raman laser phase is sensitive to the change of the Raman mirror position as shown in Eq.XII, and so we will only be considering those pulses when constructing our weighting function. To simplify the discussion we will assume 1D motion of atoms along the direction of the Raman beams.

If we consider an infinitesimal change in the Raman mirror position at time t', $dx(t')$, we can express the relative positions of the atom, $\bar{x}_j^{\rm R}$ defined in Eq. X, to be

$$\begin{aligned} &\bar{x}_j^{\rm R} \to \bar{x}_j^{\rm R}, && t_j < t'. \\ &\bar{x}_j^{\rm R} \to \bar{x}_j^{\rm R} + dx(t'), && t_j >= t'. \end{aligned} \tag{XV}$$

These changes lead to a change in the total interferometer phase, $d\Delta\phi$, which can be written using a time-domain position sensitivity function $g_x(t')$ defined by

$$d\Delta\phi = g_x(t')dx(t'). \tag{XVI}$$

Substituting Eq.XV into Eq.XI yields

$$g_x(t') = \begin{cases} +4k, & \text{if } t_2 < t' < t_3 \\ -4k, & \text{if } t_5 < t' < t_6 \\ 0, & \text{otherwise.} \end{cases} \tag{XVII}$$

The vibration-induced phase shift can be calculated

$$\begin{aligned} \delta(\Delta\phi) &= \int_{-\infty}^{+\infty} g_x(t')dx(t') \\ &= \int_{-\infty}^{+\infty} g_x(t')\frac{dx(t')}{dt'}dt' = \int_{-\infty}^{+\infty} g_x(t')v(t')dt'. \end{aligned} \tag{XVIII}$$

The position sensitivity function can also be regarded as a velocity weighting function.

If we define $g_x(t')$ as $dG(t')/dt'$ with a constraint that $G(\pm\infty) = 0$, then $\delta(\Delta\phi)$ can be written in terms of a time-dependent acceleration by

$$\begin{aligned} \delta(\Delta\phi) &= \int_{-\infty}^{+\infty} dG(t')\, v(t') \\ &= G(t')v(t')\Big|_{-\infty}^{+\infty} - \int_{-\infty}^{+\infty} G(t')\,\frac{dv(t')}{dt'}dt' \\ &= -\int_{-\infty}^{+\infty} G(t')\,a(t')\,dt' \\ &= 4k\int_{-\infty}^{+\infty} f(t')\,a(t')dt', \end{aligned} \tag{XIX}$$

where we have used integration by parts and taken $G(\pm\infty) = 0$. This gives us an acceleration weighting function $f(t') = -G(t')/(4k)$, which, with the substitutions $t_3 - t_2 = T_1$ and $t_6 - t_5 = t_3 - t_2$, is given by

$$f(t') = \begin{cases} -t', & \text{if } t_2 < t' < t_3 \\ -T_1, & \text{if } t_3 < t' < t_5 \\ (t' - t_5) - T_1, & \text{if } t_5 < t' < t_6 \\ 0, & \text{otherwise.} \end{cases} \tag{XX}$$

The weighting function $f(t')$ has a trapezoid shape for our LMT interferometer, which is different from a triangular acceleration weighting function for a standard MZ interferometer.

We note that $f(t')$ is not normalized. We define a normalization integration $\mathcal{N} = \int_{-\infty}^{+\infty} f(t')dt'$ to calculate our weighted average acceleration

$$\langle a\rangle = \int_{-\infty}^{+\infty} \frac{f(t')}{\mathcal{N}}\, a(t')dt'. \tag{XXI}$$

where $f(t')/\mathcal{N}$ is a normalized weighting function of a trapezoid shape. This is how we calculated the time-average acceleration, $\langle a(t)\rangle_{\rm LMT}$, in the main text.

GEOMETRIC EXPLANATION FOR THE SHAPE OF ACCELERATION WEIGHTING FUNCTIONS

In this section, we provide a simpler explanation for the shape of the acceleration weighting function, $f(t)$. This allows us to obtain $f(t)$ directly, rather than deriving it from the position sensitivity function.

The change in the total phase difference between the two arms, $\delta\Delta\phi$, only depends on the change of the relative position of atoms referenced to the mirror position. Let us therefore calculate the same $\delta\Delta\phi$, not in the inertial lab frame, but in the non-inertial mirror frame, where the mirror is stationary and the atoms have the additional vibrating motion. In this frame the Lagrangian of an atom, $\mathcal{L}^{\rm mirror}$, has an additional term relative to its lab-frame Lagrangian:

$$\mathcal{L}^{\rm mirror} = \mathcal{L}^{\rm lab} - \underbrace{m\,a(t)\,x}_{\mathcal{L}_\varepsilon}, \tag{XXII}$$

where $\mathcal{L}_\varepsilon$ can be understood as a linear potential $V(x) = m\,a(t)\,x$ due to a homogeneous fictitious force $-m\,a(t)$. The lab frame Lagrangian is simply given by $\mathcal{L}^{\rm lab} = m\,\dot{x}^2/2$.

As proved in the path-integral approach to atom interferometry [3], $\mathcal{L}_\varepsilon = -m\,a(t)\,x$ can be treated as a perturbation because its dependence on the spatial coordinates is less than quadratic. Hence the phase shift is obtained by integrating the perturbed Lagrangian, $\mathcal{L}_\varepsilon$,

along the unperturbed path, $\tilde{x}(t)$:

$$\begin{aligned}\delta\Delta\phi &= \Delta\phi^{\rm prop}_{\mathcal{L}_\varepsilon} \\ &= \sum_{\rm right}\int_{t_I}^{t_F}\frac{\mathcal{L}_\varepsilon}{\hbar}dt' - \sum_{\rm left}\int_{t_I}^{t_F}\frac{\mathcal{L}_\varepsilon}{\hbar}dt' \\ &= -\int_{-\infty}^{+\infty}\frac{1}{\hbar}m\left(\tilde{x}_{\rm r}(t') - \tilde{x}_\ell(t')\right)a(t')\,dt'.\end{aligned} \tag{XXIII}$$

where the unperturbed path, $\tilde{x}_{\rm r}(\tilde{x}_\ell)$, of the left (right) interferometer arm is determined by the lab frame Lagrangian, $\mathcal{L}^{\rm lab}$. These unperturbed paths $\tilde{x}_{\ell,{\rm r}}$ are illustrated in the Fig. 1 (b) in the main text.

Comparing Eq.XXIII to Eq. XIX, we find

$$f(t) = -\frac{\left(\tilde{x}_{\rm r}(t') - \tilde{x}_\ell(t')\right)}{4\hbar\,k/m}. \tag{XXIV}$$

Thus, we see $f(t)$ is proportional to the separation of the two interferometer arms, which has a trapezoidal shape for our $4\hbar$k LMT interferometer and a triangular shape for a Mach-Zehnder interferometer. The same conclusion is also applicable for a $4N\hbar$k LMT interferometer illustrated in Fig. 4 in the main text.

IN RELATION TO BRAGG TRANSISIONS

Our scheme can be undertood as a two-step Bragg transition. Figure 5(b) in the main text shows in detail how the Raman transitions give momentum to the atom. Upon absorbing a photon from one of the Raman beams, an atom of momentum p is stimulated to emit a photon of different frequency into the counter-propagating beam, thereby driving the transition $|F=1,p\rangle \rightarrow |F=2,p+2\hbar k\rangle$. The microwave pulse then returns the atom to its original internal state. The net effect is the same as that of a Bragg grating, where a photon is transferred from one beam to the other, but the internal state does not change. There, however, the photon frequencies differ only by the small recoil shift (3.77 kHz for Rb), and for pulses shorter than the inverse of this frequency, there can be a loss of atoms to higher diffraction orders [4, 5]. This is not an issue with the Raman scheme.

METHODS

We load 10^8 atoms from a 2D$^+$-MOT [6], to a 3D magneto-optical trap (MOT) of cooling light $\sim$ 16 MHz red detuned with the $(5s)^2S_{1/2}$ $F=2 \rightarrow (5p)^2P_{3/2}$ $F'=3$ transition, in addition to repump light near resonant with the $(5s)^2S_{1/2}$ $F=1 \rightarrow (5p)^2P_{3/2}$ $F'=2$ transition. Over 2 ms we ramp the frequency of our cooling laser to $\sim$ 150 MHz red detuned, then, after a further 2 ms, we ramp the intensity down to zero, releasing the atoms at near 10 μK. We then turn off the repump light, optically pumping the atoms into the $F=1$ ground state, distributed across the three m_F sublevels. Throughout the sequence, we apply we apply a Raman bias field of 0.38 G to lift the degeneracy of the m_F states.

With the intensities of the Raman beams tuned to zero the light shift, and our atoms distributed across the $m_F=-1,0,1$ sublevels, we apply a Raman π pulse to drive the $|1,0\rangle \rightarrow |2,0\rangle$ transition, before applying repumping light to pump the remaining atoms from $|1,\pm1\rangle$ to $F=2$. Another Raman π pulse transfers the atoms from $|2,0\rangle \rightarrow |1,0\rangle$, leaving the atoms in $|F,m_F\rangle = |2,m_F\neq 0\rangle$. We then apply the cooling light to selectively 'blow away' the atoms in the $F=2$ state, leaving typically 25% of the initial population, almost all in the $|1,0\rangle$ state. We do this two-step state selection as it does an element of velocity selection, too, improving our Raman Rabi flops.

The interferometer scheme is shown in the main text Fig.1 b). Our Raman microwave $\pi/2$ pulse of 51 μs places the atoms into a superposition of the two hyperfine states $|1,0\rangle$ and $|2,0\rangle$. The atoms evolve for 1 ms before we apply our first Raman π pulse of 11 μs, separating the arms of the interferometer. After T_1 = 4 ms, the second Raman π pulse of 11 μs reverses the states of the two arms and sets them on parallel trajectories, then after $T_2 = 4$ ms a microwave π pulse of 100 μs reverses their spin states while maintaining their momentum. After $T_3 = 4$ ms a Raman π pulse of 12 μs delivers another spin-dependent kick which overlaps the arms after $T_4 = 4$ ms, when we apply a final Raman π pulse of 12 μs. After a final 1 ms free evolution time we close the interferometer with a microwave $\pi/2$ pulse of 45 μs. The ratio of atoms in $F=2$ state, $P_F = 2$, at the end of the interferometer is determined by fluorescence detection.

The MEMS accelerometer (Innalabs, AI-Q-2120) is a microfabricated quartz pendulous servo accelerometer [7]. Based on the specification, we expect a noise floor of 0.24 mm/s^2 for each shot of measurement. The MEMS accelerometer is superglued to the back of the retro-reflection mirror, which tracks the vibrations of the mirror along the Raman axis. Said vibrations will be imprinted upon the atoms, and so by tracking the mirror, we are able to track the vibrations experienced by the atoms.

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